Section 25

Pulsed Plasma Thruster (PPT)

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Introduction

❖ Objectives

– Validate the ability of a new generation of PPT’s to provide precision attitude control capability
  – PPT replaces pitch wheel/torquer bar

– Confirm benign interaction
  – Demonstrate imaging capability during PPT operation

– Confirm PPT performance parameters

❖ PPT Team

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PPT Description (1 of 4)

- Opposing Thrusters
- Electronics
- Capacitor
- EO-1 Spacecraft Mounting Bracket

Earth Observing-1 Mission Technology Forum
- Small, low power, self-contained electromagnetic propulsion system
- Non-toxic solid propellant: Teflon
- High Isp (650-1350 s), very low I-bit (90-860 uN-s)
- Propellant ablated and ionized by capacitor discharge
- Plasma is accelerated by Lorentz force
- Multiple thrusters can be driven by a common capacitor
### EO-1 PPT (100 W) vs. Dawgstar PPT (10 W)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>EO-1 (Ref. AIAA-99-2276)</th>
<th>Dawgstar (Ref. AIAA-00-3256)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Input Power</td>
<td>70 Watts (one thruster—EO-1 operations)—100 Watts design</td>
<td>13.1 Watts (two thrusters at once)</td>
</tr>
<tr>
<td>Thrusters/System</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total System Impulse</td>
<td>1850 N-sec (EO-1 propel. load) &gt;15,000 N-sec (system life)</td>
<td>1125 N-sec</td>
</tr>
<tr>
<td>Impulse Bit</td>
<td>90-860 µN-sec, throttleable</td>
<td>56 µN-sec</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>8.5-56 Joules, throttleable</td>
<td>5 Joules</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>860 uN (EO-1); 1.2 mN (design)</td>
<td>112 µN</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>650-1350 sec</td>
<td>500 sec</td>
</tr>
<tr>
<td>Thrust to Power Ratio</td>
<td>12.3 µN/Watt (System Input)</td>
<td>8.3 µN/Watt (System)</td>
</tr>
<tr>
<td>Total Mass</td>
<td>4.9 kg (2 PPTs, a Power Processing Unit, and fuel)</td>
<td>3.8 kg (8 PPTs, a Power Processing Unit, and fuel)</td>
</tr>
<tr>
<td>Propellant</td>
<td>Teflon</td>
<td>Teflon</td>
</tr>
<tr>
<td>Propel. Mass (Design)</td>
<td>0.07 kg/thruster (as fueled)</td>
<td>0.030 kg/thruster</td>
</tr>
</tbody>
</table>
**EO-1 PPT Technology Advancements**

- Reduced dry mass from 6.5 to 4.8 kg through cap and electronics reductions [EO-1 PPT mass includes external mounting structure (AIAA 99-2276)]
- EO-1 PPT made significant strides in reducing electronics mass.
PPT Validation (1 of 5)

- Flight Validation scheduled for October 2001
- PPT Flight unit underwent extensive proto-flight hardware validation/development path
  - *(NASA TM-2000-210340 “Development of a PPT for the EO-1 Spacecraft”)*
    - **Functionality**: Demonstrate range of orbital operations and functionality of test support equipment
    - **Performance**: Demonstrate performance characteristics
    - **Vibration**: Acceptance level vibration testing to Delta II levels
    - **Thermal Vacuum/Cycle**: Demonstrate survival and operations across required temperature range
    - **EMI/EMC**: Measure characteristic conducted and radiated emissions and evaluate PPT susceptibility to EMI
    - **Life/Contamination**: Demonstrate thruster life capability through duration of minimum flight experiment. Evaluate plume contamination effects on spacecraft surfaces.

- Attitude control capability of PPT confirmed in high fidelity spacecraft simulations
PPT Validation (2 of 5)

- **Functionality**
  - Benchtop and vacuum testing
  - Demonstrate range of planned orbital operations
    - Throttling through charge duration control (120 - 920 msec)

- **Performance**
  AIAA-99-2290 “Multi-Axis Thrust Measurements of the EO-1 Pulsed Plasma Thruster”
  - Determine thrust and impulse bit across throttle range
    - Before and after life testing - no change
  - Evaluate off-axis impulse bit component
  - Characterize shot-to-shot repeatability
**PPT Validation (3 of 5)**

- **Vibration**
  - Acceptance level vibration testing to Delta II levels
    - Random vibration to 14.1 grms on 3 axes

- **Thermal Vacuum**
  - Demonstrate survival and operations across required temperature range
    - -32 to +42°C survival range
    - -15 to +42°C operating range
  - Characterized sensitivity in main capacitor charge rate to temperature
    - Factored into performance results
    - Function of charge duration throttling approach

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**PPT Discharge Energy at Varying Temperatures**

- 15°C
- +25°C
- +42°C
PPT Validation (4 of 5)

- **Life/Contamination**
  - Demonstrate thruster life
    - Minimum experiment life (100,000 pulses/side)
  - Evaluate plume contamination effects on spacecraft surfaces.
    - Spacecraft surface samples (X-band antenna surface, radiator, MLI)

- **EMI/EMC:**
  - Characterised conducted and radiated emissions
    - Consistent with previous electric propulsion devices
    - RE01, CE01 and CE07 results within spec
    - CE03 limits (conducted emissions) exceed by up to 12 dB below 4 MHz – waiver accepted
  - RE02 broadband radiated emissions exceed levels below 100 MHz
    - AIAA 2001-3641 “Addressing EO-1 Spacecraft PPT EMI Concerns”
  - Continuing PPT EMI evaluation at GRC
PPT Validation (5 of 5)

- **Attitude Control Experiment**
  - PPT Replaces pitch momentum wheel
  - Minimum impact to existing ACS architecture
  - Same PID controller used
    - Computed pitch torque commands processed for PPT control
    - PID control gains adjusted
  - Pitch wheel speed brought to zero
    - Pitch magnetic torquer turned off

- **Simulation Results**
  - During imaging mode pointing errors within 5 arcsec requirement
  - Worst case roll, pitch, and yaw errors: 52.1, 129.3, 14.2 arcsec
    - Caused by solar array wind/rewind
  - Orbital average power 12.6 W
PPT Technology Transfer & Infusion

Current (EO-1) → Near Term (DawgStar, StarLight) → Far Term (TPF, MAXIM)

Multi-Thruster System Architecture, Long Life, Low Mass/Volume, Integration Ease, Specific Impulse, Efficiency, Thrust-to-Power, Impulse Bit Accuracy

Continued PPT Technology Development and Improvement
Formation Flying

- **Interferometry Missions (Starlight, TPF, Planet Imager)**
  - Require 1 cm separation control between spacecraft
  - PPTs have been leading candidates for these missions due to high precision thrust pulses, high Isp

- **Earth Observing Mission (Techsat 21, Leonardo)**
  - Air Force and NASA are studying ways to deploy constellations of small satellites in co-orbiting formations
  - Typically requires 1 mN - 100 mN of thrust, with capability to generate 0.5 mN - 2 mN-s impulse bit
  - PPTs trade well because of small impulse bit, high Isp, and small volume

**Precision Pointing (Maxium)**
- Fine attitude control for pointing optical instruments
Continuous disturbance reduction

- **Drag free control (GRACE and GPS follow-ons)**
  - Repeatable low thrust range of PPT use to cancel atmospheric drag forces
  - Maintains orbit, improves prediction accuracy
- **Other (TDRSS type GEO missions)**
  - PPTs can cancel disturbance forces to reduce size of attitude control system

**Micro/Nanosats (Dawgstar, MMS)**

- Low mass/volume/power ideally suited for microsats
- Simple to integrate, No chemical/pressure hazard
  - Well suited multiple S/C on a deplorer ship and university project

**Large Space Structures**

- Used as active control actuators
Lessons Learned

- **PPTs can be implemented as attitude control actuators with minimal impact to existing attitude control subsystem architectures**

- **Increasing range of PPT thrust would expand the use of PPT as ACS actuators**
  - On going PPT development efforts are addressing concern by looking at changes to components and changes in operation methods

- **Radiated emission concerns must be addressed earlier in project timeline**
  - Special test with PPT in bell jar while electrically mated to S/C to confirmed benign effect on S/C bus (without instruments).
  - Successful ambient testing with GSE performed with ALI integrated
  - Effort to conclusively quantify risk to instruments unit beyond program constraints at time issue was identified
    - Most desirable solution for EO-1 would be to test with high fidelity ALI engineering unit

- **Continuing research into PPT EMI reduction leveraging EO-1 experience**
  - Addressing: lower discharge energies, improved component characteristics, geometry effects, sparkplug characteristics
Summary / Conclusion

- **Benefits of PPT Technology**
  - Micro impulse capability for precision pointing/positioning
  - Unique high \( I_{sp} \), low power attributes well suited to small spacecraft
  - Eliminates distributed, toxic propellant systems
  - Low mass / power / volume alternative for mission in which both conventional ACS and delta-V systems can be replaced.

- **Applications**
  - Formation flying/precision pointing (Starlight, SAR, TPF, Maxium)
  - Propulsive attitude and drag free control (Future GRACE/GPS missions, GEO solar disturbances)
  - Micro/small satellite propulsion (Dawgstar, Techsat 21)

- **EO-1 Flight Validation**
  - EO-1 PPT experiment will validate the capability of a new generation of PPTs to perform spacecraft attitude control
  - Ground validation tests indicate adequate PPT performance